Journal of Coastal Research | 12 | 4 | 831–840 | Fort Lauderdale, Florida | Fall 1996

Tsunami as a Major Control on Coastal Evolution, Southeastern Australia

Edward A. Bryant, Robert W. Young and David M. Price

Dept. of Geography
University of Wollongong
Northfields Avenue
Wollongong, New South Wales 2522
Australia

ABSTRACT

BRYANT, E.A.; YOUNG, R.W., and PRICE, D.M., 1996. Tsunami as a major control on coastal evolution, southeastern Australia. *Journal of Coastal Research*, 12(4), 831–840. Fort Lauderdale (Florida), ISSN 0749-0208.

General concepts of coastal evolution of the southeastern Australian coastline during the Late Pleistocene involve barrier formation by wind and swell waves during marine transgressions and formation of rock platforms by chemical and mechanical weathering at rates of 1–5 mm yr^{-1}. Where evidence indicates rapid change, storms are often invoked as the causative mechanism. These concepts ignore the important role of a repetitive, rapid, catastrophic tsunami in both coastal erosion and accretion. The impact of a tsunami can be distinguished by four signatures: uncemented clastic deposits; boulders that are imbricated, stacked and uniformly aligned; constructional features; and erosional bedrock sculpturing. The boulder deposits occur at elevations above both the measured and theorised limits of storm-wave action. Bedrock sculpturing has not been attributed previously to marine processes but rather to catastrophic water flow from icesheets or ice-dammed lakes, a phenomenon which has never influenced the mainland coast of Australia during the Pleistocene. Thermoluminescence dating has shown that tsunamis in southeastern Australia, while eroding most Last Interglacial and interstadial barriers, have also contributed to the construction of many present barriers. They have also shaped the rocky coast by modifying raised platforms and in extreme cases ripping enormous slabs of bedrock from promontories and cliff faces up to heights of 40–50 m. A change in emphasis in the current thinking regarding the processes responsible for coastal evolution is needed in coastal geomorphology to include the impact of repetitive tsunamis which are capable of dramatically and irrevocably modifying a landscape over very short periods of time.

ADDITIONAL INDEX WORDS: *s-forms, bedrock sculpturing, catastrophic waves, thermoluminescence dating, barriers, platforms, cliffs.*

INTRODUCTION

At first sight, the New South Wales South coast appears unlikely to have been affected by rapid change during the Late Quaternary. The coast from Sydney south to Kioloa Beach (Figure 1) is cut almost entirely in the gently dipping Permo-Triassic rocks of the Sydney Basin. Along most of this section of the coastline, there is a close coincidence of topography with the dip of the rock, so that coastal features often exhibit structural control. South to the Victorian border, the coastline is cut mainly in the metamorphic and crystalline rocks of the Lachlan Fold Belt and structural control is less evident. The descent of mid-Oligocene (30 ma) basalts to approximately modern sea level, the presence of sediments of Oligocene age at modern sea level, the occurrence of Early Miocene estuarine deposits at the level predicted by worldwide sea-level curves, Oligocene silcrete and Miocene laterite descending to modern sea level, deep kaolinisation of probably Late Cretaceous to Early Tertiary age at elevations as low as +50 m, and the outcrop of Cretaceous trachytic lavas and tuffs at modern sea level comprise a compelling array of evidence attesting to long term tectonic stability of the coastline (YOUNG and BRYANT, 1993). Analysis of the Last Interglacial, Stage 5e high sea-level stillstand for Australia indicates that the New South Wales coastline forms a hinge line for tectonic warping of the Australian plate (BRYANT, 1992). While substantial uplift has occurred southwards into Victoria and Tasmania, Stage 5e sea-levels along the New South Wales South coast were no more than 4–6 m higher than present, a fact supported by field evidence and in agreement with the worldwide reference level for that time (YOUNG *et al.*, 1993b). Finally, unlike the temperate coasts of the Northern hemisphere, the coastline has not been affected by glacial ice or outwash during the Pleistocene.

Tsunami have been identified as a significant geomorphic process along the South coast at high sea-level stillstands during the Late Pleistocene (YOUNG and BRYANT, 1992; BRYANT *et al.*, 1992a, 1995; BRYANT and PRICE, 1995). The term tsunami is used in the broadest sense to refer to any repetitive and suddenly generated wave having a period greater than 60 s and a height at shore in excess of 2 m. Tsunami have acted at two scales depending not only upon the configuration of the coast, but also upon the magnitude of the tsunamigenic event. At the smaller scale, beaches have been overwashed, boulders re-deposited in aligned imbricated piles and bedrock surfaces sculptured (BRYANT, *et al.*, 1992;

95052 received and accepted in revision 30 May 1995.

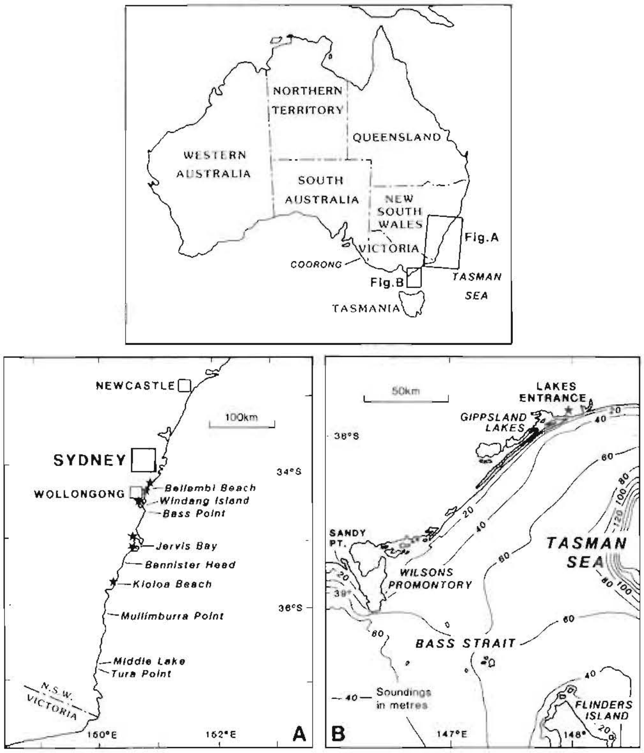

Figure 1. Location map of the New South Wales South coast and Gippsland Lakes region of Victoria. *—location of anomalous tsunami deposits dated around 22–26 ka.

YOUNG and BRYANT, 1992; YOUNG *et al.*, 1995). At the larger scale, ramps have been formed or extensively modified along cliffs, the ends of headlands rising over 20 m above sea-level have been truncated and pre-Holocene marine barriers eroded so that only scattered remnants are preserved (YOUNG and BRYANT, 1993; BRYANT *et al.*, 1995). This activity has occurred repetitively over the last 110 ka, with one event taking place at the end of the Last Interglacial and at least 3 events taking place during the Late Holocene (YOUNG and BRYANT, 1992; BRYANT *et al.*, 1992a). The geomorphic signature of tsunami impact is so well organised and defined that it is unusual that it has not been recognised along other coastlines of the world. This paper summarises the evidence for repetitive tsunami reworking of the coastline of southern New South Wales and also of the Gippsland Lakes region of Victoria (Figure 1). Based on this evidence, there is a need for a change in emphasis in coastal geomorphology, from an approach which assumes that coastlines are formed by gradualistic processes to one which considers the inheritance of catastrophic events such as tsunamis upon coastal landscapes and their subsequent modification by low magnitude processes.

THE GEOMORPHIC SIGNATURE OF TSUNAMI

The signature of tsunami impact upon the coastal landscape can be grouped under four broad headings: uncemented clastic deposits; boulders that are imbricated, stacked and uniformly aligned; constructional features; and erosional bedrock sculpturing. While the classification is based upon evidence obtained from the southeastern coast of Australia, various attributes have been documented elsewhere in the world.

Uncemented Clastic Deposits

Tsunamis can transport a range of sorted and unsorted clastic sediment to the coast. These include widespread sand layers deposited in marshland, mixtures of sand and boulders, and boulder piles (DAWSON, 1994). The deposition of pure sand in layers over lowlands has been widely reported for Scotland (DAWSON *et al.*, 1988), the west coast of the United States (ATWATER, 1987; DARIENZO and PETERSON, 1990) and Canada (CLAGUE and BOBROWSKY, 1994). Units tend to consist of one or two distinct laminae (DAWSON *et al.*, 1991). Only one deposit of this type has so far been identified in New South Wales (BRYANT *et al.*, 1992a). More commonly in New South Wales, sand layers less than 1.5 m thick and containing isolated boulders have been linked to tsunamis (BRYANT, *et al.*, 1992a and b; YOUNG *et al.*, 1995). While such deposits may also be formed by storm waves superimposed upon storm surges during tropical cyclones (for example during Hurricane Iniki in Hawaii in 1992, THE HONOLULU ADVERTISER, 1992), the New South Wales deposits can extend to elevations of 20 m above sea level well above the maximum storm surge limits of 1.0–1.5 m measured or theorized for the coast (BRYANT, 1991). Chaotic mixes of sediment containing boulders are also well documented for both modern and inferred tsunami deposits (MOORE and MOORE, 1988; DAWSON, 1994; MOORE *et al.*, 1994). Similar deposits, often mixed with shell are extensively preserved along the New South Wales coastline (BRYANT *et al.*, 1992a).

Boulder Fabric

Imbricated and aligned boulder deposits indicative of tsunami transport have only been reported so far from the New South Wales coastline (YOUNG *et al.*, 1995). Here boulders up to 49 m^3 in size, weighing as much as 90 tonnes and requiring tractive forces exceeding 100 kg/m^2 have been shifted, imbricated and stacked on top of each other in a step fashion at Jervis Bay during the Late Holocene. These fabric characteristics cannot be readily attributed to swell or storm waves but are analogous to boulder deposits formed by large-scale unidirectional flows in fluvial environments (KESEL and LOWE, 1987). Such deposits appear at the top of cliffs 33 m above present sea-level. These altitudes exclude storm waves which even during the 1 in 80 year storm of 1974 did not surge over platforms 7–8 m above sea-level. Tsunamis appear more appropriate as a mechanism to lift such large blocks to the top of these high cliffs and to produce the observed stacking.

Constructional Features

A tsunami has also been proposed as being responsible for the formation of a range of constructional features along the New South Wales coastline. Sand lamina often form wide,

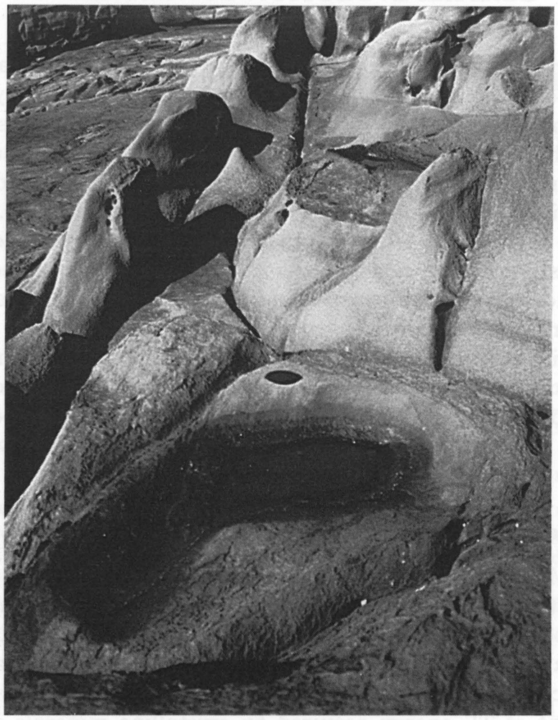

Figure 2. Examples of some of the sculptured *s-forms* produced by the tsunami event at Tura Point. The flutes are situated on the north face of a 14 m high cliff facing the tsunami which came in from the northeast. Superimposed on the sides of the flutes are cavettos. A muschelbruch *s-form,* subsequently modified by weathering, lies in the foreground. The camera lens cap on the muschelbruch rim is for scale.

Figure 3. The arrow marks a canyon structure cut through the 20 m high headland at Atcheson Rock at Bass Point. This canyon has a northeast to southwest orientation that is not structurally controlled and which parallels the alignment of other canyon structures in the area. YOUNG and BRYANT (1993) linked these features to a large tsunami (probably the Tura event) approaching the coast in the photograph from the bottom left. Evidence exists in the cutting for subsequent downcutting of 2–4 m by a Holocene tsunami, sweeping along the coast from the southeast. The direction of this event is linked to the orientation of imbricated and aligned boulders stacked along cliffs at Jervis Bay, 50 km south (YOUNG *et al.,* 1995). The latter event also draped a chaotically sorted boulder, sand, shell layer 0.5–2 m thick over the headland to the right of the gap. The TL age of the sand is 2.3–4.3 ka (W1782–83); the radiocarbon age of the shell is 0.77 ka (Beta78894).

splayed barrier units, while sand and cobbles have been moulded into mounds, beach ridges and chenier-like features dating as Late Holocene in age (BRYANT *et al.,* 1992a). Many forms could easily be mistaken for ice-pushed or wind-wave built features. However, the coastline has never been affected by ice during the Pleistocene let alone the Holocene. Many forms also appear in sheltered environments where refracted swell simply did not have the energy required to construct the forms (BRYANT *et al.,* 1992a). The constructional features, which were apparently emplaced under repetitive tsunamis, can account for a significant portion of some Holocene coastal barriers and estuarine infills.

Erosional Bedrock Sculpturing

The erosional aspects of tsunamis are imperfectly documented and poorly understood. On the small scale, tsunami jetting and overwashing of bedrock surfaces can generate vortices that sculpture bedrock in the same manner as has been documented for unidirectional, high velocity flow commonly associated with sub-glacial environments (SHAW, 1988; SHARPE and SHAW, 1989; KOR *et al.,* 1991) or mega-floods originating from glacial icesheets (BAKER, 1981). Such sculptured forms have been labelled *s-forms* (KOR *et al.,* 1991) and were first attributed to tsunamis along the New South Wales coastline by YOUNG and BRYANT (1992). Since then the complete suite of *s-forms* described for sub-glaciated landscapes (KOR *et al.,* 1991) has been found on tsunami swept headlands and platforms along the New South Wales coastline. The forms include muschelbrüche, sichelwannen, cavettos, flutes and cavitation marks (Figure 2). The features are both a product of the Last Interglacial and Holocene tsunami events and are often orientated in the same direction as associated tsunamigenic boulder deposits along the adjacent coastline (YOUNG *et al.,* 1995). A complete description is not possible here and will be reported in greater detail elsewhere.

Not only are tsunamis capable of generating smoothed bedrock sculptured features; but on a larger scale, they are also responsible for some of the cliff and headland morphology present along the coast (YOUNG and BRYANT, 1993). In extreme cases, tsunamis, such as the one which deposited boulders 33 m above sea-level at Jervis Bay, also swamped clifflines ripping slabs of bedrock up to 6 m in diameter from promontories and cliff faces as high as 40–50 m above sea level (Figure 4). Tsunami sculptured terrain is characterised by irregular bedrock landforms developed on headlands usually rising more than 5 m above sea level. The headlands have inherited morphology produced by long term erosional weathering processes and probably repeated tsunami events. The largest tsunami event identified to date is the Tura Point event attributed to a cataclysmic landslide from the island of Hawaii about 105 ka (MOORE *et al.,* 1989). This slide swept sediment to elevations of 326 m above present sea-level on the Island of Lanai, and deposited 3 beds of boulder debris to elevations of 50 m (MOORE and MOORE, 1984). YOUNG and BRYANT (1992) postulated that the slide also sent a wave into the south Tasman

Figure 4. Cliff erosion due to a Holocene tsunami event from the southeast at Little Beecroft Head on the north side of Jervis Bay. North is at the top of the photograph. The headland in the background extends 35 m above sea-level. Normally imbricated blocks up to 2 m in length were deposited at the top of the headland (YOUNG *et al.*, 1995). Blocks up to 6 m in length have been ripped off the cliff face by tsunami and shoved into the gully separating the headland from the main cliffline.

Sea that overran headlands to elevations of at least 16 m. While the type location is Tura Point, erosion is manifest along the coast at Mullimburra Point, Bannister Head, Bass Point and Windang Island (Figure 1). The event produced or greatly modified ramps that extend from modern sea level to heights of 30 m, often along vertical cliff faces (YOUNG and BRYANT, 1993). High velocity overwashing stripped the ramp surfaces by generating lift forces that plucked joint-controlled rock slabs from the underlying bedrock.

Sometimes, flow either accelerated under the effects of gravity and jetted down the steeper sides of some headlands or was focused by wave refraction effects. Where this has occurred, erosive channelisation has produced cutting at the back of some raised platforms YOUNG and BRYANT (1992). Linear canyon features 2–7 m deep or pool-and-cascade features incised into resistant bedrock have formed on the lee side of steep headlands (Figure 3). The features preserve crude indicators of the direction of tsunami approach in that they tend to dip downslope parallel to the inferred direction of flow. In some cases, it is difficult to determine whether the erosion at the back of headlands represents flow channelisation or simply the erosive impact of enormous waves breaking over headlands. Thus, many platforms evidence a raised ramp or butte-like structure at their seaward edge separated from the shoreline by an eroded depression. The forms are best developed at Windang Island, Atcheson Rock south of Bass Point (Figure 3), Kittys Point south of Jervis Bay and Durras Beach south of Kioloa. No other explanation has yet been found in the literature to account for the generation of these detached forms other than by catastrophic tsunami wave impact.

COASTAL EVOLUTION CONTROLLED BY TSUNAMI

Identification of remnant Pleistocene and Holocene marine deposits shows that such features were once extensively developed along this coast and that their destruction, as hypothesised here by tsunamis, left behind either stranded estuarine plains or highly dissected but overlapping sand deposits (BRYANT *et al.*, 1995; BRYANT and PRICE, 1995). For the New South Wales South coast, this process has left a coastline whose sandy portions have been interpreted as sand-starved and recessional (THOM, 1983). In some instances, dated barrier sands appear anomalous with Late Pleistocene humate sandwiched between Holocene beach and estuarine deposits. The patterns of sedimentation do not fit into the standard model for barrier construction defined for the eastern Australian swell-dominated wave regime (YOUNG *et al.*, 1993a).

Thermoluminescence Dating Technique

Much of the stratigraphic re-interpretation has been supported by the usage of thermoluminescence (TL) dating of deposits supplemented by conventional radiocarbon methods (BRYANT, *et al.*, 1992a, b; YOUNG, *et al.*, 1993a). The dating of coastal sediments using TL is based upon the measurement of TL energy acquired by crystalline minerals since their burial within a sedimentary unit. The technique used here is essentially the combined regenerative/additive method of READHEAD (1984) applied to the 90–125 micron quartz fraction. More complete descriptions of the technique can be found in BRYANT, *et al.* (1990) and PAGE *et al.* (1991). TL has always been viewed as subject to a number of uncertainties: a) incompleteness of bleaching prior to deposition; b) variations in long-term water content; c) possible fluctuations in dose rates due to weathering; or d) differential leaching of uranium and thorium (HUNTLEY, 1985; NOTT and PRICE, 1991). However, recently the accuracy of TL has been assessed favourably against other dating techniques such as ^{14}C and uranium/thorium over a timespan of at least 65 ka (NANSON, *et al.*, 1991). In near-coastal regions TL has been found to correspond, within the error of the technique, to stratigraphically determined interglacial barrier chronologies over the past 800 ka (HUNTLEY *et al.*, 1993).

The greatest discrepancies in TL dating are produced by partial bleaching and mobilisation of uranium and thorium; but if these problems exist, they generally make the apparent age of a sediment older. For instance in the well-drained, raised marine sediments dated here, radioactive elements are more likely to be leached from the sand bodies than to accumulate within them if they become mobile. Thus, a Holocene dune or barrier may yield a Late Pleistocene age when in fact it has formed within the last 10 ka. The presence of a temperature plateau that includes the 325–375°C range, used in calculating a TL age, can be used to assess the degree of bleaching and the quality of the final age determination (PRICE, 1994). Over 90% of the TL dates reported here display a temperature plateau incorporating this band and hence were not incompletely bleached.

When interpreting the TL ages of most of the marine coast-

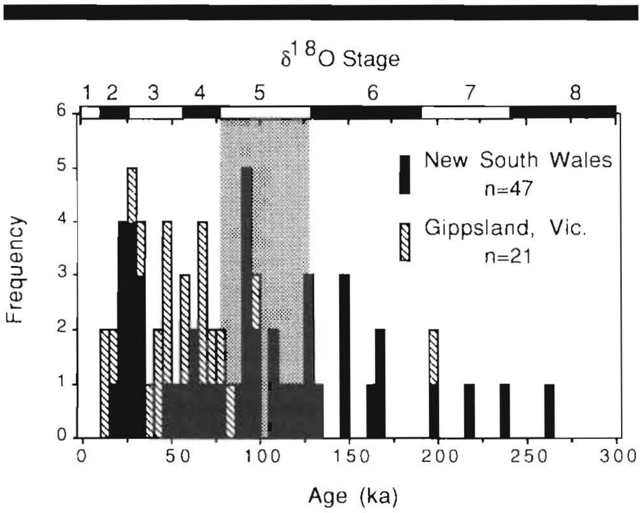

Figure 5. Histogram of TL age determinations of Late Pleistocene marine coastal deposits between 12–300 ka for the Gippsland lakes region and New South Wales coast. Glacial and interglacial stages as defined by the global palaeo-temperature $\delta^{18}O$ curve (MARTINSON *et al.*, 1987) are added for reference. The period covering the Last Interglacial is shaded.

al barrier ages reported here, the ages should be viewed as maximum ones. Additionally, there has been no surface residual TL correction applied to any date; modern environmental equivalents for many sand bodies were not locally present. Note that the one standard deviation placed upon the TL dates is much greater than that usually reported for ^{14}C dates, because it attempts to incorporate the total experimental, environmental as well as the statistical uncertainty assigned to each TL parameter, and not just the statistical uncertainty of the measurement technique. A histogram of TL ages of marine deposits in southeastern Australia is plotted in Figure 5. This figure is a composite of published work and differentiates the ages of New South Wales barriers (BRYANT, *et al.*, 1995) from those of the Gippsland Lakes region of Victoria (BRYANT and PRICE, 1995). The global timing and duration of glacial and interglacial events, based upon the $\delta^{18}O$ chronology of MARTINSON *et al.* (1987), is depicted for reference at the top of Figure 5. The period of the Last Interglacial, when most Pleistocene barriers in the region are interpreted as having been formed, has been shaded. Note too that in the following discussion the accepted peak for the Last Glacial Maximum is taken as 22 ka based upon U/Th mass spectrometry dating of corals (BARD *et al.*, 1990). TL and ^{14}C ages, quoted specifically in the text, are also summarised in Tables 1 and 2 respectively.

Chronostratigraphic Evidence for Tsunami

The New South Wales South coast, which is one of tectonic stability over the Late Quaternary as described above, is dominated by remnant barriers often less than 100 m in length and usually tucked into sheltered positions (BRYANT, *et al.*, 1995). The remnants have erosional bluffs on their sea-

Table 1. *Thermoluminescence dates used in distinguishing suspect tsunami deposits in southeastern Australia*

Sample No.	Depositional Environment	Palaeodose (grays)	K (%)	Th and U Chains (Bq/kg)	Annual Dose (μgrays)	Temperature Plateau (°C)	TL Age × ka	Standard Deviation × ka
Bellambi Beach								
W1213	tsunami overwash	31.0 ± 3.7	0.63	31.5 ± 4.0	1208 ± 63	350–500	25.6	3.3
W1214	Holocene beach	21.2 ± 2.4	0.22	127 ± 4.0	2867 ± 74	275–375	7.4	0.8
W1295	tsunami overwash	19.4 ± 1.6	0.37	17.8 ± 4.0	884 ± 74	300–500	22.0	2.6
W1296	tsunami overwash	24.4 ± 3.4	0.18	40.9 ± 4.0	1108 ± 72	275–500	22.0	3.4
W1297	tsunami overwash	17.3 ± 1.7	0.33	13.7 ± 4.0	752 ± 73	275–500	23.0	3.2
W1402*	pumice	37.3 ± 9.0	0.65	9.3 ± 0.3	1477 ± 70	300–375	25.2	6.2
Atcheson Rock								
W1782	tsunami overwash	3.2 ± 0.4	0.09	24.1 ± 0.8	742 ± 51	300–400	4.3	0.6
W1783	tsunami overwash	1.5 ± 0.2	0.11	18.2 ± 0.5	636 ± 50	300–375	2.3	0.4
Kioloa Beach								
W1642	tsunami overwash	19.6 ± 2.8	0.10	29.8 ± 0.9	779 ± 46	275–400	25.2	3.9
W1664	estuarine	7.0 ± 0.5	0.10	41.5 ± 1.3	821 ± 40	275–400	8.7	0.8
Gippsland Lakes								
W1257	marine barrier	19.3 ± 0.7	0.83	8.0 ± 0.3	1036 ± 43	275–425	18.6	1
W1434	barrier dune	68.4 ± 6.6	0.47	20.2 ± 0.6	1047 ± 50	275–500	65.4	7
W1435	barrier dune	70.4 ± 5.4	0.50	24.7 ± 0.8	1183 ± 51	300–500	59.5	5.2
W1436	beach ridge	20.0 ± 2.0	0.06	17.2 ± 0.5	547 ± 49	275–500	36.5	4.8
W1437	raised beach	216 ± 29.0	0.60	14.4 ± 0.4	1084 ± 50	350–500	199.0	28
W1555	marine barrier	39.7 ± 3.8	0.04	14.4 ± 0.5	469 ± 48	300–450	84.6	11.9
W1655	spit barrier	28.2 ± 3.7	0.08	22.4 ± 0.7	678 ± 50	300–500	41.7	6.2

[1] Cosmic contribution to annual radiation dose assumed to be 150 μgrays unless indicated. Specific activity levels measured by calibrated thick source alpha counting over a 42 mm scintillation screen assuming secular equilibrium

[2] K and Rb levels determined by XRF

[3] All TL determinations are carried out on 90–120 microns quartz sand fraction except where indicated

*Fine grain additive technique used

Table 2. *Radiocarbon ages used in constraining the age of tsunami deposits in southeastern Australia. Error terms are reported to 1 standard deviation.*

Laboratory No.	Depositional Environment	Sample Type	Measured ^{14}C Age × ka	C^{13}/C^{12} Ratio	Conventional ^{14}C Age × ka
Beta43951	estuarine	*Tapes watlingi* *Plebidonax deltoides*	6.1 ± 0.08	1.0 ‰	6.6 ± 0.08
Beta78894	tsunami overwash	*Cabestana spengleri*	0.33 ± 0.06	1.7 ‰	0.77 ± 0.06

Ages are environmentally adjusted for ocean reservoir effect by 0.56 ± 0.08 ka
Error terms are reported to 1 standard deviation

ward side. The modal age for the barriers is the Last Interglacial (Figure 5). Indeed, it is not difficult to find well defined barrier exposures dating not only at the perceived Substage 5e sea-level peak of 125 ka, but also lying at an elevation of at least 3 m above present sea-level (YOUNG, *et al.*, 1993b). However, a significant number of barriers date at Sub-stage 5a and more importantly younger than 80 ka.

In contrast, the Gippsland Lakes coast has undergone uplift exceeding 105 mm ka^{-1} over the Late Pleistocene (BRYANT and PRICE, 1995). The coastline consists of two parallel barriers labelled the "Inner" and "Outer" barrier and interpreted respectively as Late Pleistocene and Holocene in age (Figure 6). In actual fact, the Gippsland barriers are composite features consisting of smaller sand bodies that have eroded and reformed over the last 80 ka, preferentially at times of interstadial sea-level stillstands (Figure 6). The barriers themselves are not scarped, but appear as subdued features that in places have been overwashed by later depositional events. For example at Sandy Point (Figure 1), a Late Pleistocene barrier dating at 84.6 ± 11.9 ka (W1555) and lying at an elevation of 15 m above present sea level, is backed 5 km further inland by a younger barrier system lying at an elevation of 20 meters and dating at 41.7 ± 6.2 ka (W1655). Additionally at Sperm Whale Head, the Inner Barrier is backed by two beaches situated on the mainland at Bark Hill at elevations of 5 and 8 m above sea-level (Figure 6). The Inner barrier dated as old as 65 ka (W1434–35), but one of the raised beaches yielded a TL age of only 14.3 ± 1.1 ka (W1437).

The presence of TL ages younger than the Last Interglacial Sub-stage 5e peak cannot be put down to failure of the TL dating technique. The same methodology has detected the existence of more than one Sub-stage 5e barrier along the coast (YOUNG, *et al.*, 1993b; BRYANT, *et al.*, 1995), and has dated accurately the Coorong Barrier sequence in South Australia back to 800 ka (HUNTLEY *et al.*, 1993). In New South Wales, it appears that barrier erosion has occurred since Sub-stage 5e and has been focused differentially along the coast so that some older barrier remnants have been preserved. Subsequent recovery phases occurred mainly during Sub-stage 5a with minor rebuilding during later stillstands. In the Gippsland Lakes region, where preservation of barriers should have been aided by the fact that the coastline has been undergoing continuous uplift, hardly any Last Interglacial barriers remain. Here abundant fluvial sand supplies have allowed barriers to form repeatedly inland of the present coastline during interstadials (Figure 6). This fact is anomalous because, even with the rates of rapid uplift occurring in the region, interstadial sea levels should be lower than present ones.

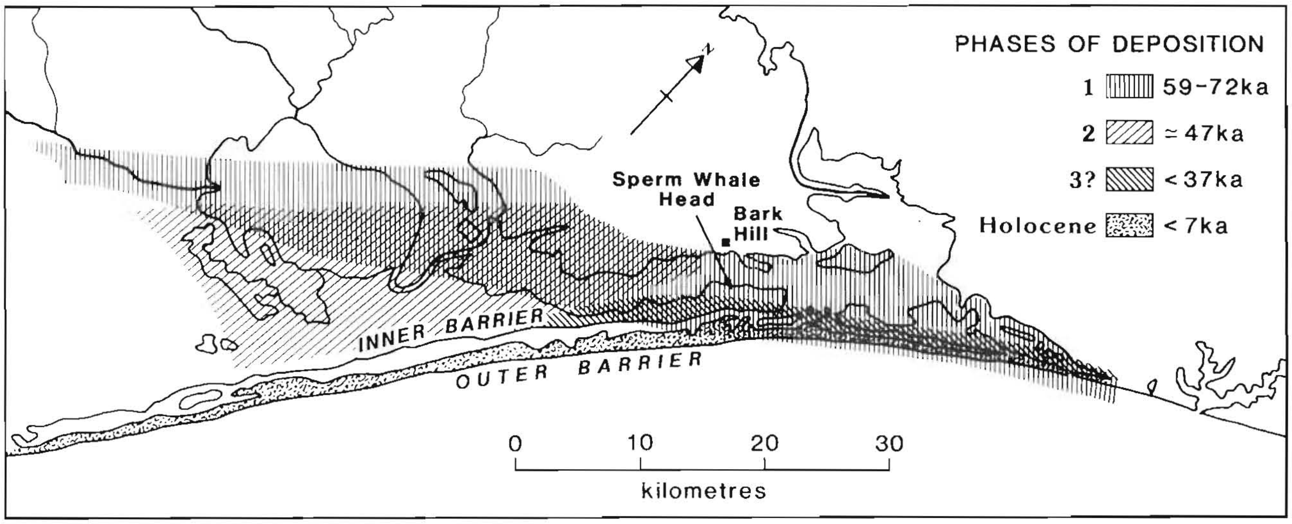

Figure 6. Evolutionary model of Late Pleistocene barrier development of the Gippsland Lakes. Four intermittent phases of overlapping barrier erosion and subsequent reconstruction have occurred since the Last Interglacial.

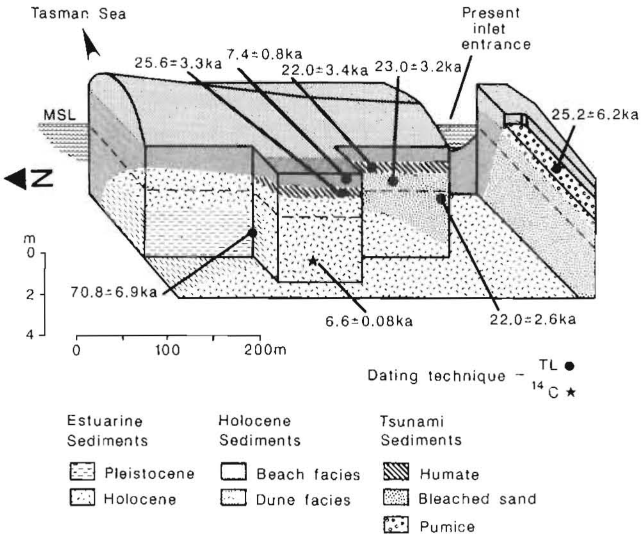

Figure 7. Schematic stratigraphy and chronology of the Holocene barrier partially built by tsunami overwash at Bellambi, Wollongong, New South Wales.

The mechanism accounting for the pattern of erosion and barrier preservation in both regions is hypothesised as being repetitive catastrophic tsunamis. In New South Wales, the associate of barrier remnants along coastline with elevated, aligned boulder deposits and bedrock sculptured terrain supports this hypothesis. In the Gippsland Lakes, the effective extraction of Last Interglacial barriers, the overrunning of barriers, and the repeated deposition of interstadial barriers at or above present sea level requires swamping of the coastline that only catastrophic tsunami could provide.

In both regions, there is evidence that tsunami have been involved in the accretion of barriers as well. The evidence is characterised by the presence of anomalous marine deposits dating mainly around 22–26 ka and lying in juxtaposition with Holocene sediments near present sea level. Atypical deposits so far have been found at eight locations around the southeastern Australian coastline from Wollongong to Lakes Entrance (Figure 1). The age of the deposits do not represent the time of deposition as sea levels were up to 130 m lower at this time. The best site displaying anomalous deposition can be found at Bellambi Beach, Wollongong (Figure 7). Here a 1.0–1.2 m thick humate beach sand containing isolated rounded boulders lies on top of Holocene estuarine clay which is overlain by Holocene beach sand. The Holocene clay yielded a radiocarbon age of 6.6 ± 0.08 ka (Beta 43951) from estuarine shell (*Tapes watlingi, Plebidonax deltoides*), while the Holocene sand gave a TL age of 7.4 ± 0.8 ka (W1214). The humate in between was dated at four locations and gave TL ages between 22.0–25.6 ka (W1213, W1295–97, maximum standard deviation = 3.4). Moreover a TL determination was made on a 20–30 cm thick pumice layer which had floated onto the humate near the southern inlet. The pumice yielded an age of 25.2 ± 6.2 ka (W1402). The TL age of the pumice is important because it represents both a different resetting process and a different technique of analysis from that applied to the marine quartz sands. The pumice has been absolutely zeroed because of volcanic heating, while the quartz sands have been rezeroed by solar bleaching. In addition, the pumice was analysed using the fine-grain technique on the 2 micron fraction, while the sands were analysed using the coarse-grain technique on the 90–125 micron fraction. The similar age between the pumice and the tsunami sands gives credibility to the 22–26 ka Last Glacial age estimated for the deposit. However, it does not explain why sediments are deposited at present sea level along a coast that is tectonically stable, when sea levels during the Last Glacial should have been much lower. The sequence can be interpreted as representing the impact of a tsunami after 6.6 ka (radiocarbon years). This tsunami swept relict Last Glacial beach sediment, bypassed by the Holocene transgression, shoreward from the shelf. In the process, the tsunami entrained boulder material from a headland 1 km away. The transport of sand was so rapid that none of the sand was bleached of its TL signal. The sediment consisted mainly of beach sand because it contained pumice which was refloated to the surface of the sea by the tsunami disturbance. The sand was deposited on top of Holocene estuarine clay along the modern shoreline, but at a sea-level elevation that was about 2 m higher than present. Being coated with organics, the sand was recemented into humate. The freed pumice drifted into the lagoon on sea breezes and was sealed in by the return of sand to the beach following the tsunami event.

The basic humate sequence occurs at other locations along the southeastern coast. At Kioloa, New South Wales, estuarine clay is again overlain by a 1.7 m thick splay of humate capped by beach and Holocene dune sands containing heavy mineral layers. The estuarine clay yielded a TL age of 8.7 ± 1.7 ka while the overlying humate dated at 25.2 ± 3.4 ka. At the east end of the Gippsland Lakes, similar anomalous humate sands appear in beach ridges. The sands date between 18.6 and 36.5 ka (W1257 and W1436 respectively), are humate cemented, and are positioned at the same elevation as Holocene marine sediments.

DISCUSSION

At first sight, the southeastern coast of Australia seems unlikely to have preserved the imprint of catastrophic tsunami documented above. Historically, the Sydney tide gauge has recorded tsunami heights of only 1.0 m in 1868 and 1877 and 0.8 m in 1960 (BRYANT, 1991). No records except for Aboriginal myths exist before European settlement in 1786. The southeastern Australian coastline is also far removed from current Pacific Ocean zones of tsunami activity (WOODS and OKAL, 1987) and appears seismically inactive historically, at least at a level sufficient to generate tsunamis locally.

In the past, rapid coastal change, especially in sandy sediments, has been explained by invoking storms (THOM, 1974; BRYANT, 1988; MORTON, 1988). Where sediments have previously incorporated boulders, the role of storms versus tsunami has become problematic (BOURROUILH-LE JAN and TALANDIER, 1985; BRYANT *et al.,* 1992a; JONES and HUNTER, 1992;

DAWSON, 1994). However, much of the latter debate deals with isolated boulders or boulders chaotically mixed with sand deposited on low lying coastal plains or atolls. The pattern of stacked and aligned boulders along the New South Wales coast has never been linked in the literature to storm waves or surges, but rather to large floods (YOUNG, *et al.*, 1995). Additionally, much of the latter evidence occurs along rocky coastlines or on top of cliffs 33 m high. More importantly, even a casual reconnaissance of the New South Wales rocky coastline will show that storms are inadequate in accounting for the bedrock sculptured features dominating the rocky coast. The uniform alignment of such forms, often not structurally controlled, also rules out chemical weathering. The largest storms measured this century in 1974 and 1978 generated deep water waves of only 10.2 m height, while the maximum probable wave for the coast is only a few meters higher (YOULL, 1981). The effectiveness of these wave heights cannot be exacerbated at shore by storm surges because the narrowness of the shelf and nature of storms limits surges here to less than 1.5 m (BRYANT, 1991). In addition, storm wave periods rarely exceed 15 s and then for only very short durations. Waves bigger than this, but more importantly of several minutes duration, are required to account for the sustained high velocity flows required to sculpture highly resistant bedrock. Tsunamis appear to be the only mechanism capable of providing these conditions along the coast.

The source of the tsunami responsible for the features described in this paper have yet to be defined and located with certainty. The prime source, without doubt for events from the southeast, would appear to be the Macquarie Ridge at the edge of the Australian plate southwest of New Zealand. The region has generated 12 earthquakes with magnitudes greater than or equal to Ms 7.0 between 1920–84 (JONES and MCCUE, 1988). Macquarie Ridge has historically produced numerous small tsunamis measured on tide gauges along the southeastern coast of the continent; however rarely have wave heights exceeded 0.1 m. Refraction analysis however indicates that tsunami waves from here will impinge preferentially along the southeastern coast of New South Wales. Earthquakes along Macquarie Ridge theoretically have the capability of generating a wave train consisting of 70–100 individual waves which can significantly impact upon the coastline. Such a source is all the more likely and effective for the Gippsland Lakes given the region's closer proximity and the funnelling effect of bathymetric contours leading from the Tasman Sea into Bass Strait, nor can volcanic activity be ruled out. An active volcano, which has received little study, exists at 40°S in the Tasman Sea (MCCUE, Pers. Comm., 1993).

However earthquakes and volcanoes, while perceived globally as the cause of most tsunamis, may not be sufficient to generate the type of superwaves which the sedimentary and erosional evidence in New South Wales demands. Underwater sediment slides, comets and meteorite impacts are all possible mechanisms in the Tasman Sea region. While distant underwater slides such as the Lanai event in Hawaii have been invoked to account for the erosion and bedrock sculpturing at Tura Point (YOUNG and BRYANT, 1992), local slides off the Australian continental shelf cannot be ruled out. Recently, super-sidescan acoustic imaging by the Australian Geological Survey Organisation has detected the presence of a very large landslide, measuring 10 × 20 km, on the continental slope 35 km offshore from Bellambi (JENKINS and RAWSON, 1994–95). While undated, this slide would be a prime candidate for the tsunami that deposited older shelf sediment described above on the Holocene barrier along the adjacent coast (Figure 7). Finally, bedrock sculpturing on rock platforms has not been documented in the literature outside Australia as a feature produced by earthquake-generated tsunami. In near-glacial environments, such features require flow velocities of 5–10 $m\ s^{-1}$ to form (BAKER, 1981; KOR, *et al.*, 1991). Superwaves have exceeded these velocities. For example the Lituya Bay Alaskan earthquake and resulting landslide of 1958 generated a tsunami that surged 525 m above sea level and obtained velocities of 210 $km\ hr^{-1}$ (HUGGETT, 1989). However, this event was contained within an inlet and flow velocities were not sustained for any length of time. Hence, the wave only produced surficial stripping of bedrock. Given the presence of sculptured bedrock along 300 km of the New South Wales coastline, a bigger type of event is necessary and the impact of a comet or meteorite into the Tasman Sea cannot be dismissed. HUGGETT (1989) has calculated that the impact of an object as small as 0.83 km in diameter striking an ocean could produce superwaves 50 m or more high travelling at speeds in excess of 200 $m\ sec^{-1}$. Even an object with a diameter of only 0.2 km entering the Tasman Sea could produce run-up 10–100 m high. The occurrence of such events is not that rare in terms of the Late Quaternary. An extraterrestrial object, 0.2 km in size, has a theoretical recurrence interval for the Pacific Ocean of 24–43,000 years (HUGGETT, 1989).

The events in southeastern Australia are repetitive throughout the Late Quaternary. Based upon thermoluminescence dating and stratigraphic mapping, one large event occurred at the end of the Last Interglacial along the New South Wales coast (YOUNG and BRYANT, 1992, 1993). Thermoluminescence dating of barrier sediments in the Gippsland Lakes region suggests that other events took place there throughout the Late Quaternary probably around times of interstadial sea-level high stillstands (BRYANT and PRICE, 1995). Evidence in both regions suggests that the coastline was swamped again shortly after sea-level reached its present level around 7 ka. Anomalously aged Late Glacial sand has onlapped the coast and has been covered or blocked from the ocean by Holocene sand. Other evidence exists suggesting that tsunamis affected embayments along the coast around 3 ka (BRYANT, *et al.*, 1992a). Recently, a deposit of mixed sand and boulders deposited from suspension flow was found at elevations greater than 20 m at Atcheson Rock (Figure 3). This sand forms part of the evidence, reported above, for a major tsunami event affecting the coast from the southeast. The TL age of this sand is less than 4.3 ± 0.6 ka (W1782–83); however a ^{14}C age of 0.77 ± 0.06 ka (Beta 78894) was obtained from a marine shell, *Cabestana spengleri*, lying within the deposit. Similarly, young radiocarbon dates have been obtained from other suspect tsunami deposits in the region (BRYANT, *et al.*, 1992a), and it now appears likely the most recent large event occurred along the South coast within the last 800 years.

There is no reason why the evidence for the role of repetitive tsunamis in coastal evolution described here for southeastern Australia should not have more universal relevance. Other coastlines have far better defined events producing large tsunami than the southeastern coast of Australia. The North Sea coastline was affected by the Storegga slide (DAWSON *et al*, 1988; HARBITZ, 1992), the islands in the Hawaiian region were swept by mega-slides throughout the Pleistocene (MOORE and MOORE, 1988; MOORE *et al.*, 1994); on the Sanriku coast and Ryukyu Islands of Japan (OTA, *et al.*, 1985; MINOURA and NAKAYA, 1991; MINOURA *et al.*, 1994) and the western North American coastline tsunami sedimentation has been documented for the Late Holocene (ATWATER, 1987; DARIENZO and PETERSON, 1990; CLAGUE and BOBROWSKY, 1994). These areas should be examined systematically and more broadly for supportive evidence.

More importantly, the evidence found in southeastern Australia for tsunamis comes from the very coastline where gradualist concepts of coastal processes have been defined. The beaches of southeastern Australia provided the field evidence for the conceptualisation of reflective-dissipative morphodynamic and sedimentological models (BRYANT, 1982; SHORT and WRIGHT, 1984; SHORT, 1986). These concepts may have little relevance to the long term evolution of the coastline. Additionally, the views expressed in the literature on the formation of coastal rock platforms and clifflines may be in need of revision. While chemical and mechanical weathering processes operating at rates of 1–5 mm yr^{-1} are perceived in the literature as the main mechanisms shaping rocky coasts (TRENHAILE, 1987; SUNAMURA, 1992), most of the bedrock coastline of southeastern Australia is relict, having been shaped over the space of several days by catastrophic waves, in some cases up to 100 ka ago without significant modification since. The models of bedrock sculpturing attributed to catastrophic flow in near-glacial environments explain better the coastal geomorphology of the southeastern Australian rocky coastline than the concepts presently outlined in the coastal literature.

Finally, models of barrier formation that have been formulated for the coastline may need revision (YOUNG et al., 1993a). Transgressive barriers are theorised to have formed either as the result of the postglacial marine transgression or as a response to coastal processes at present sea-level. Barriers are formed at a stable sea level over the last 6.5 ka in a complex manner with interfingering of nearshore, washover and lagoonal facies. The Bellambi barrier is a striking exception to these models. Not only is the barrier not recessional, but it also consists of interfingering of Holocene sediment and Pleistocene beach sand transported in bulk from the shelf by tsunami. In the case of the Gippsland Lakes, the barriers appear to represent significant accretion by tsunami overwash, not only at present day sea-levels but also during interstadial high sea level stillstands.

CONCLUSIONS

The existing concepts of gradualism in coastal geomorphology encompassing beach processes, barrier construction and rocky shoreline erosion apparently are limited in explaining the long-term evolution of the coastline of southeastern Australia. The coastal landscape here is mainly inherited, being the product of repetitive, rapid, catastrophic wave overwashing and erosion of the coast. Tsunamis, rather than storms, appear the more likely mechanism. If the most recent large tsunami event to strike the coastline is as recent as 800 years ago, then the geomorphic change being measured today represents a certain degree of post-tsunami recovery. It is hoped that the evidence summarised here will initiate a change in emphasis in the current thinking about the mechanisms responsible for the evolution of coastlines during the Late Quaternary and Holocene, especially for coastlines that may have been subject to repetitive tsunami impact. In short, the recognition of well-documented catastrophic flow events that have revolutionised fluvial geomorphology over the last two decades (BAKER, 1981) should be considered as a viable alternate explanation to storms in coastal geomorphology.

ACKNOWLEDGEMENTS

Thermoluminescence dating was assisted by José Abrantes. Funding was provided by the University of Wollongong through the Quaternary Research Programme. Dr. John Shaw, University of Alberta and Dr. Keith Tinkler, Brock University, provided valuable information and discussion about bedrock sculpturing. Dr. Wally Johnson and Mr. Kevin McCue of the Australian Geological Survey Organisation provided information on the possible sources of tsunamis in the Tasman Sea. Mr. David Martin and Mr. Richard Miller aided with cartography, while Penny Williamson prepared the photographs. Dr. Ian Shennan, University of Durham, Dr. Alastair Dawson, Coventry University and an anonymous referee made valuable comments and suggestions on the manuscript.

LITERATURE CITED

ATWATER, B.F., 1987. Evidence for great earthquakes along the outer coast of Washington state. *Science*, 236, 942–944.

BAKER, V.R. (ed.), 1981. *Catastrophic Flooding: The origin of the channeled scabland.* Stroudsburg: Dowden, Hutchinson and Ross, 360p.

BARD, E.; HAMELIN, B.; FAIRBANKS, R.G., and ZINDLER, A., 1990. Calibration of the ^{14}C timescale over the past 30,000 years using mass spectrometric U-Th ages from Barbados corals. *Nature*, 345, 405–410.

BOURROUILH-LE JAN, F.G. and TALANDIER, J., 1985. Sédimentation et fracturation de haute énergie en milieu récifal: Tsunamis, ouragans et cyclones et leurs effets sur la sédimentologie et la géomorphologie d'un atoll: Motu et Hoa, à Rangiroa, Tuamotu, Pacifique SE. *Marine Geology*, 67, 263–333.

BRYANT, E. A., 1982. Behaviour of grain size characteristics on reflective and dissipative foreshores, Broken Bay, Australia. *Journal of Sedimentary Petrology*, 52, 431–450.

BRYANT, E.A., 1988. Storminess and high tide beach change, Stanwell Park, Australia 1943–1978. *Marine Geology*, 79, 171–187.

BRYANT, E.A., 1991. *Natural Hazards*. Melbourne: Cambridge University Press, 294p.

BRYANT, E.A., 1992. Last Interglacial and Holocene trends in sea-level maxima around Australia: implications for modern rates. *Marine Geology*, 108, 209–217.

BRYANT, E.A. and PRICE, D.M., 1995. Late Pleistocene marine chronology of the Gippsland Lakes region, Victoria. (in review).

BRYANT, E.A.; YOUNG, R.W., and PRICE, D.M., 1992a. Evidence of tsunami sedimentation on the southeastern coast of Australia. *Journal Geology,* 100, 753–765.

Bryant, E.A.; Young, R.W., and Price, D.M., 1995. Late Pleistocene Marine Deposition and TL Chronology of the New South Wales, Australian Coastline. *Zeitschrift für Geomorphologie N.F.* (in press)

Bryant E.A.; Young R.W.; Price D.M., and Short S.A., 1990. Thermoluminescence and uranium-thorium chronologies of Pleistocene coastal landforms of the Illawarra region, New South Wales. *Australian Geographer,* 21, 101–112.

Bryant, E.A.; Young, R.W.; Price, D.M., and Short, S.A., 1992b. Evidence for Pleistocene and Holocene raised marine deposits, Sandon Point, New South Wales. *Australian Journal of Earth Science,* 39, 484–493.

Clague, J.J. and Bobrowsky, P.T., 1994. Evidence for a Large Earthquake and Tsunami 100–400 Years Ago on Western Vancouver Island, British Columbia. *Quaternary Research,* 41, 176–184.

Darienzo, M.E. and Peterson, C.D., 1990. Episodic Tectonic Subsidence of Late Holocene Salt Marshes, Northern Oregon Central Cascadia Margin. *Tectonics,* 9, 1–22.

Dawson, A.G., 1994. Geomorphological effects of tsunami run-up and backwash. *Geomorphology,* 10, 83–94.

Dawson, A.G.; Foster, I.D.L.; Shi, S.; Smith, D.E., and Long, D., 1991. The identification of tsunami deposits in coastal sediment sequences. *Science of Tsunami Hazards,* 9, 73–82.

Dawson, A.G.; Long, D., and Smith, D.E., 1988. The Storegga Slides: Evidence from Eastern Scotland for a Possible Tsunami. *Marine Geology,* 82, 271–276.

Harbitz, C.B., 1992. Model simulations of tsunamis generated by the Storegga Slides. *Marine Geology,* 105, 1–21.

Huggett, R., 1989. *Cataclysms and Earth History.* Oxford: Clarendon, 220p.

Huntley, D.J., 1985. On the zeroing of the thermoluminescence of sediments. *Physics and Chemistry of Minerals,* 12, 122–127.

Huntley, D.J.; Hutton, J.T., and Prescott, J.R., 1993. The stranded beach-dune sequence of south-east South Australia: a test of thermoluminescence dating, 0–800 Ka. *Quaternary Science Review,* 12, 1–20.

Jenkins, C. and Rawson, A., 1994–95. A GIS of the Australian Seabed. *GIS USER,* November 1994–January 1995, 33–34.

Jones, B. and Hunter, I.G., 1992. Very large boulders on the coast of Grand Cayman: The effects of giant waves on rocky coastlines. *Journal of Coastal Research,* 8, 763–774.

Jones, T.D. and K.F. McCue, 1988. The seismicity and tectonics of the Macquarie Ridge. *Papers and Proceedings of the Royal Society Tasmania,* 122, 52–57.

Kesel, R.H. and Lowe, D.R., 1987. Geomorphology and sedimentology of the Toro Amarillo alluvial fan in a humid tropical environment, Costa Rica. *Geografiska Annaler,* 69A, 85–99.

Kor, P.S.G.; Shaw, J., and Sharpe, D.R., 1991. Erosion of bedrock by subglacial meltwater, Georgian Bay, Ontario: a regional view. *Canadian Journal of Earth Science,* 28, 623–642.

Martinson, D.G.; Pisias, N.G.; Hays, J.D.; Imbrie, J.; Moore, T.C., and Shackleton, N.J., 1987. Age dating and the orbital theory of the ice ages: Development of a high-resolution 0 to 300,000-year chronostratigraphy. *Quaternary Research,* 27, 1–29.

Minoura, K. and Nakaya, S., 1991. Traces of tsunami preserved in inter-tidal lacustrine and marsh deposits: some examples from Northeast Japan. *Journal of Geology,* 99, 265–287.

Minoura, K.; Nakaya, S., and Uchida, M., 1994. Tsunami deposits in a lacustrine sequence of the Sanriku coast, Northeast Japan. *Sedimentary Geology,* 89, 25–31.

Moore, G.W. and Moore, J.G., 1988. Large-scale bedforms in boulder gravel produced by giant waves in Hawaii. *Geological Society of America, Special Paper No. 229,* pp. 101–110.

Moore, J.G. and Moore, G.W., 1984. Deposit from a giant wave on the island of Lanai, Hawaii. *Science,* 226, 1312–1315.

Moore, J.G.; Bryan, W.B., and Ludwig, K.R., 1994. Chaotic deposition by a giant wave, Molokai, Hawaii. *Geological Society of America Bulletin,* 106, 962–967.

Moore, J.G.; Clague, D.A.; Holcomb, R.T.; Lipman, P.W.; Normark, W.R., and Torresan, M.E., 1989. Prodigious submarine landslides on the Hawaiian ridge. *Journal of Geophysical Research,* 94, 17465–17484.

Morton, R.A., 1988. Nearshore responses to great storms. *Geological Society of America, Special Paper No. 229,* pp. 7–22.

Nanson, G.C.; Price, D.M.; Short, S.A.; Young, R.W., and Jones, B.G., 1991. Comparative uranium-thorium and thermoluminescence dating of weathered Quaternary alluvium in the tropics of northern Australia. *Quaternary Research,* 35, 347–366.

Nott, J.F. and Price, D.M., 1991. Late Pleistocene to early Holocene aeolian activity in the Upper and Middle Shoalhaven Catchment, New South Wales. *Australian Geographer,* 22, 168–177.

Ota, Y.; Pirazzoli, P.A.; Kawana, T., and Moriwaki, H., 1985. Late Holocene coastal morphology and sea-level records on three small islands, the South Ryukyus, Japan. *Geographical Review of Japan,* 58B, 185–194.

Page, K.J.; Nanson, G.C., and Price, D.M., 1991. Thermoluminescence chronology of Late Quaternary deposition on the Riverine Plain of southeastern Australia. *Australian Geographer,* 22, 14–23.

Price, D.M., 1994. TL dating of fluvial quartz sands: a comparison of ages obtained at 325°C and 375 °C. *Ancient TL* (in press).

Readhead, M.L., 1984. Thermoluminescence Dating of Some Australian Sedimentary Deposits. Unpublished PhD dissertation, Australian National University, Canberra.

Sharpe, D.R. and Shaw, J., 1989. Erosion of bedrock by subglacial meltwater, Cantley, Quebec. *Geological Society of America Bulletin,* 101, 1011–1020.

Shaw, J., 1988. Subglacial erosional marks, Wilton Creek, Ontario. *Canadian Journal of Earth Science,* 25, 1256–1267.

Short, A.D., 1986. Sandy shore facies in southeast Australia: a general sequence of sediments, bedforms and structures. *Geological Society of Australia New South Wales Division, Publication No. 2,* pp. 87–100.

Short, A.D. Wright, L.D., 1984. Morphodynamics of high energy beaches: an Australia perspective. *In:* Thom, B.G. (ed.), *Coastal Geomorphology in Australia.* Sydney: Academic, pp. 43–68.

Sunamura, T., 1992. *Geomorphology of Rocky Coasts.* New York: Wiley, 302p.

The Honolulu Advertiser, 1992. *Hurricane Iniki.* 95p.

Thom, B.G., 1974. Coastal erosion in eastern Australia. *Search,* 5, 198–209.

Thom, B.G., 1983. Transgressive and regressive stratigraphies of coastal sand barriers in southeast Australia. *Marine Geology,* 56, 137–158.

Trenhaile, A.S., 1987. *The Geomorphology of Rock Coasts.* Oxford: Clarendon Press, 384p.

Woods, M.T. and Okal, E.A., 1987. Effect of variable bathymetry on the amplitude of teleseismic tsunamis: a ray-tracing experiment. *Geophysical Research Letters,* 14, 765–768.

Youll, P.H., 1981. Botany Bay waverider system-Ten Years of Records. *Proceedings of the Fifth Australian Conference on Coastal and Ocean Engineering,* Sydney, Australian Institute of Engineers, pp. 245–251.

Young, R. and Bryant, E., 1992. Catastrophic wave erosion on the southeastern coast of Australia: Impact of the Lanai tsunami ca. 105 ka? *Geology,* 20, 199–202.

Young, R.W. and Bryant, E.A., 1993. Coastal rock platforms and ramps of Pleistocene and Tertiary age in Southern New South Wales, Australia. *Zeitschrift fur Geomorph N.F.,* 37, 257–272.

Young, R.W.; Bryant, E.A.; Price, D.M.; Wirth, L.M., and Pease, L.M., 1993a. Theoretical constraints and chronological evidence of Holocene coastal development in central and southern New South Wales, Australia. *Geomorphology,* 7, 317–329.

Young, R.W.; Bryant, E.A., and Price, D.M., 1993b. Last Interglacial sea levels on the South coast of New South Wales. *Australian Geographer,* 24, 72–75.

Young, R.W.; Bryant, E.A., and Price, D.M., 1995. Catastrophic wave (tsunami?) transport of boulders in southern New South Wales, Australia. *Zeitschrift für Geomorphologie* N.F. (in press).